

Recent Ground Hold and Rapid Depressurization Testing of Multilayer Systems

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In the development of flight insulation systems for large cryogenic orbital storage (spray on foam and multilayer insulation), testing need include all environments that are experienced during flight. While large efforts have been expended on studying, bounding, and modeling the orbital performance of the insulation systems, little effort has been expended on the ground hold and ascent phases of a mission. Historical cryogenic in-space systems that have flown have been able to ignore these phases of flight due to the insulation system being within a vacuum jacket. In the development phase of the Nuclear Mars Vehicle and the Shuttle Nuclear Vehicle, several insulation systems were evaluated for the full mission cycle. Since that time there had been minimal work on these phases of flight until the Constellation program began investigating cryogenic service modules and long duration upper stages. With the inception of the Cryogenic Propellant Storage and Transfer Technology Demonstration Mission, a specific need was seen for the data and as such, several tests were added to the Cryogenic Boil-off Reduction System liquid hydrogen test matrix to provide more data on a insulation system. Testing was attempted with both gaseous nitrogen (GN₂) and gaseous helium (GHe) backfills. The initial tests with nitrogen backfill were not successfully completed due to nitrogen liquefaction and solidification preventing the rapid pumpdown of the vacuum chamber. Subsequent helium backfill tests were successful and showed minimal degradation. The results are compared to the historical data.

Nomenclature

0	=	initial state
c_p	=	specific heat, J/kg/K
f	=	final state
h	=	specific enthalpy, J/kg
i	=	discrete time steps within a summation
j	=	discrete volume spaces within the tank
k	=	discrete section of tank surface
liq	=	liquid temperature, K
m	=	mass, kg
t	=	time, s
T	=	temperature, K
t_0	=	initial time step, $t = 0$
T_{exit}	=	temperature of gas exiting the tank or control volume, K
Q	=	energy, J
\dot{V}	=	volumetric flow rate, m ³ /s
ρ	=	density, kg/m ³

I. Introduction

CRYOGENIC propellants including liquid hydrogen and liquid methane in combination with liquid oxygen provide the highest specific impulse of any reasonable propellant combination for chemical propulsion. As such, these propellant combinations are often sought out for use in upper stages and other in-space applications to

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maximize payload delivery for a given launch mass. Since not all missions allow for propellant usage in the first few hours of flight, long duration cryogenic storage (from 10 hours to several years) of propellant on-orbit has long been viewed as an enabling capability for the development of in-space assets. A requirements for long duration cryogenic storage is a high performance insulation system. One high performance insulation system type is multilayer insulation (MLI), often referred to as superinsulation.

Over the years many different entities have studied the performance of MLI in a high vacuum for space applications.¹⁻⁷ Fewer have studied MLI performance in an atmosphere of pressure and fewer yet have studied MLI performance during the rapidly decreasing pressure experienced during launch where its thermal performance is orders of magnitude worse than on orbit. The evacuation of the MLI is a complex phenomenon that can drive the performance of the insulation for days after launch as all of the gas slowly leaves the thin spaces in between reflector layers built into the MLI. Instead of driving out all the details with the time dependencies of these phenomena, for a first order analysis, it is often easier to characterize this additional heat load as an integrated heat leak (see Figure 1).

Multiple science payloads such as Wide-Field Infrared Survey Explorer (WISE), Superfluid Helium On-Orbit Transfer (SHOOT), Gravity Probe B, and the Cosmic Background Explorer (COBE) have used small amounts of various cryogenic fluids such as hydrogen or helium lasting for up to five years.⁸⁻⁹ However, these payloads are small enough to use vacuum vessels around the cryogenic tank to mitigate need to understand the rapid evacuation of the MLI during launch, ascent, and the transition to on-orbit steady state thermal performance. In a non-vacuum jacketed tank, these phases add an extra heat load to the system.

Initial large scale MLI plans from the 1960s and 1970s performed rapid evacuation testing and gained a level of understanding of the rapid dynamics at play during rapid depressurization.¹⁰⁻¹⁴ That understanding has diminished over the years as the conquering of low earth orbit was the main goal of human exploration. In the past ten years, NASA has begun to improve upon the understanding of the transient performance of newer MLI systems and the resulting effect that these loads have on the performance of MLI in space. In 2009, NASA and Ball Aerospace partnered on liquid nitrogen testing of Ball Aerospace's high performance insulation system. In 2010, NASA performed the Methane Lunar Surface Thermal Control (MLSTC) testing, which also included a rapid depressurization test on a 48 inch diameter spherical test article. Work was done by NASA in 2011 studying ambient temperature effects of multiple gasses evacuating from MLI systems. In 2013, NASA performed several depressurization tests during the Cryogenic Boil-off Reduction System liquid hydrogen testing. A summary of all test tanks is shown in Table 1.

As NASA prepares for the Cryogenic Propellant Storage and Transfer (CPST) Technology Demonstration Mission, an understanding of the rapid depressurization of MLI systems will be required to ensure that enough propellant gets to orbit for the storage and transfer demonstration. The understanding and the testing and shortcomings that are always encountered in ground testing will be put to the test before the demonstration can commence.

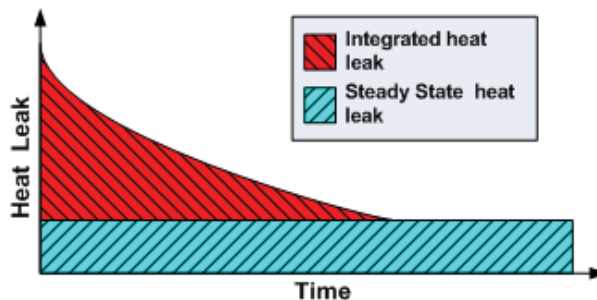


Figure 1. Integrated Heat Leak over a notional flight timeline.

II. Early Testing

Early development and testing of large scale MLI was done in preparation for the Modular Nuclear Vehicle. As MLI development progressed from basic understanding of performance to design and fabrication for large tanks, the understanding of the performance of MLI through all mission phases. Due to the large range and rapidly changing heat loads MLI systems experience between ambient pressure and high vacuum, heat load measurements were not always taken. However, on each of the tests, something interesting was recorded, and combined they give a reasonable overview of a wide body of knowledge.

A. Lockheed, 1968¹⁰

In 1967, Lockheed was given a contract to study the design of large scale multilayer insulation systems for a long duration upper stage of the Modular Nuclear Vehicle. A large portion of their contract was focused on evacuation of the blanket, both analytically and experimentally.

Table 1. Summary of rapid depressurization test geometries.

Test Name	Tank Size (m)	# MLI Layers	MLI Thickness (cm)	Foam	Cryogen/ Test Fluid	Purge Gas
CBRS	1.2	49	6.0	2 – 10 cm	Hydrogen	Helium
MLI-BAC Venting	1.5 plate	66	~5	No	None	Nitrogen Argon
MLSTC	1.2	60	6.0	No	Methane	Nitrogen
Ball Aerospace	1.2	40	4.7	No	Nitrogen	Nitrogen Helium
NASA Marshall	3.05	45	3.8	3.5 cm	Hydrogen	Nitrogen
NASA Lewis	1.39	30	1.7	No	Hydrogen	Helium
General Dynamics	2.21	44	4.0	No	Hydrogen	Helium
McDonnell Douglas	2.67	70	1.8	No	Hydrogen	Helium
Lockheed	0.38	115	3.8	No	Hydrogen	Helium

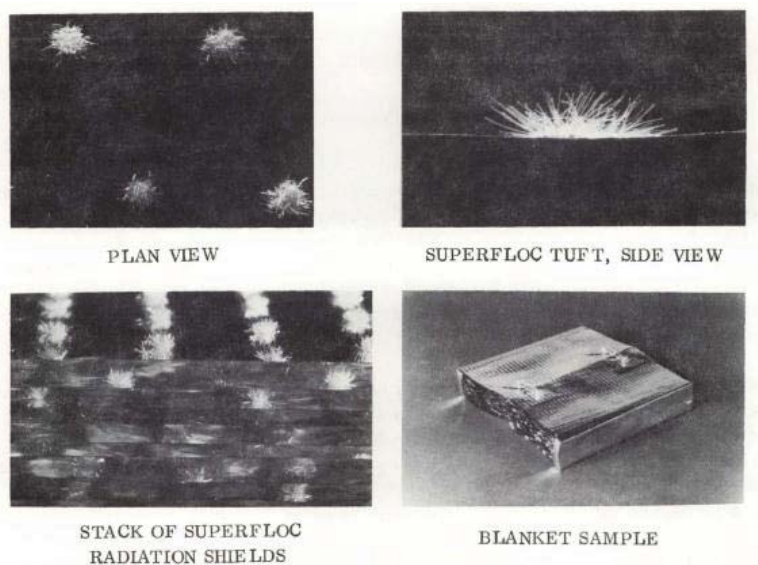
For their subscale evacuation testing, a 1.8 m (72 inch) long by 0.38 m (15 inch) diameter calorimeter was used. The analysis of the flow paths of the gas out of the blanket compared to their full scale design indicated that the flow path resistance was similar to or greater than the actual application. A 115 layer blanket, 38 mm (1.5 inch) thick blanket made of double aluminized Mylar and tissueglass was applied on the calorimeter for testing with liquid hydrogen and at ambient temperature. The blanket was made of three sub-blankets, each closed out with a butt-seam that was offset 25 mm (1 inch) from the one below it.

Measurements included thermocouples within the MLI blanket and pressure transducers also within the MLI blankets. The pressure was read between each of the three blankets and referenced to the vacuum chamber using delta Pressure transducers at the “no flow boundary” or furthest location from a seam.

Testing was performed both with liquid hydrogen as a cold sink in the calorimeter and with no cold sink in the calorimeter. It was expected that the pressure differentials would be higher at the ambient temperature than with the liquid hydrogen cold sink due to the decrease in helium viscosity with decreasing temperature. Testing on the ambient temperature test showed a maximum differential pressure of 0.62 torr within the first 20-50 seconds of depressurization. The pressure differentials during the liquid hydrogen sink test were lost due to a leak in the sense line. The temperature sensors never leveled off in the 22 hours of testing. It was noted that after about 100 seconds, the vacuum pump could not keep up with the desired pressure profile.

B. McDonnell Douglas, 1973¹¹

McDonnell Douglas was awarded a contract for the development of a MLI system for the 105 inch diameter liquid hydrogen tank at MSFC. The tank was 2.67 m (105 inches) in diameter and was filled to a depth of approximately 2.75 m (108 inches), though the tank and insulation system were longer than that. The final MLI system selected for installation was a 70 layer blanket using double-aluminized Mylar

**Figure 2: Photos of Superfloc (credit General Dynamics)**

reflectors and Dacron B4A netting spacers. While the target layer density of the blanket was 30 layer/cm, the final installation layer density ended up being 39 layer/cm due to a fabrication inconsistency within the netting procured for the tank installation compared to the netting previously used. Two different tests were run, the first was a thermal test following a slow pumpdown of the vacuum chamber, the second test was a rapid depressurization test that was followed by a steady state thermal test. It was noted that the heating rate in the second steady state thermal test was 50% higher than in the first test. Post test examination of the blanket showed no indication of damage and the difference was written off as an increase in trapped gas pressure between the warm and cold evacuations as excess water vapor was measured degassing after the rapid depressurization using a residual gas analyzer. The transient period after launch lasted for 50 hours before steady state was observed.

It is also of interest to note that an insulation system based on this development work was flown on the forward dome of the Skylab module. The performance of the 48 layer gored MLI installed on the forward dome appears to have been nominal ($1.3 - 2.2 \text{ W/m}^2$ on the outer surface of Skylab), though the performance had a wide variation due to the method of measurement on orbit. While no degradation over the first 6 months was observed, it was noted that the method of measurement was not precise enough to determine if degradation was present.¹²

C. General Dynamics, 1975¹³

General Dynamics was awarded a series of contracts to develop their MLI product called Superfloc. Superfloc consisted of tufts of Dacron needles between double goldized mylar radiation shields as shown in Figure 2. The system was designed with a helium purge bag around 45 layers of Superfloc on a 2.21 m (87 inch) diameter tank. The goal of the testing was to demonstrate that the MLI could survive 100 evacuation and repress cycles (similar to pressure cycles that might be experienced on the Space Shuttle) while installed on a tank filled with liquid hydrogen. After 20 cycles an approximately 26% increase in total heat load was seen. After 51 cycles (the degradation was observed to have leveled off), damage was repaired on a seam and the system rebaked out prior to the final 48 cycles being completed. The repair on the seam returned the orbital heat load within 10% of the original heat load and another 10% degradation was seen during the last 48 cycles. The data is shown graphically in Figure 3.

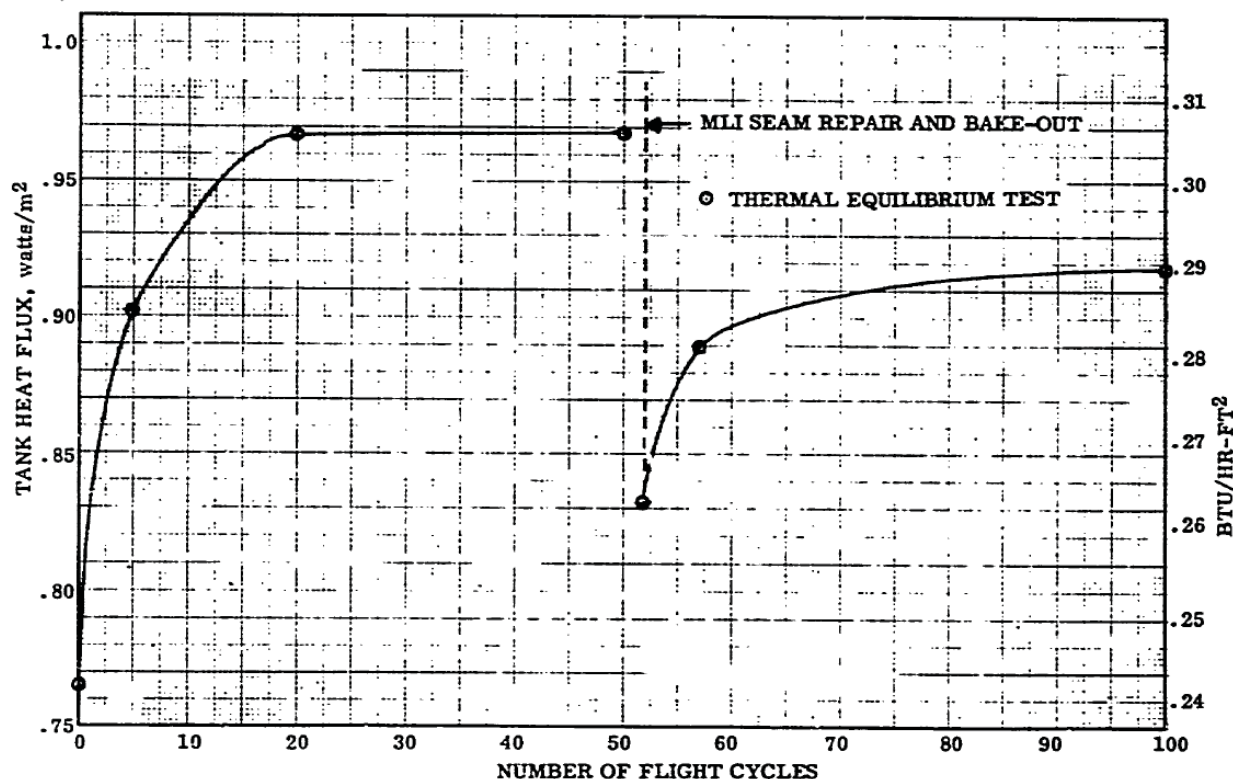


Figure 3. Effect of multiple rapid depressurizations on a single insulation system.

D. Lewis Research Center, 1978¹⁴

Testing was done at Lewis Research Center on a 1.39 m diameter spherical tank using liquid hydrogen. The spherical tank had 2 sub-blankets of 15 layers each of double aluminized mylar and double aluminized mylar scrim

cloth covers separated by a single layer of silk net at a layer density of 17.7 layer/cm. Helium was used to actively purge the MLI so that no foam was necessary. No purge bag was used as it was assumed that the fairing surrounding the vehicle would act as such a containment device. The test matrix consisted of 19 depressurization cycles at various conditions including the addition of water to the helium purge gas. This testing showed the most rapid adjustment of the flow to the rapid depressurization of the MLI on any of the tests. The data indicated that the blanket came to steady state over the course of a few hours. While a post test inspection of the blanket revealed no damage to the blanket, the final orbital thermal performance test indicated minimal damage (12% total degradation from initial testing) from the repeated pressure cycles. The heat load with the tank at one atmosphere was 620 W/m^2 and mostly independent of purge flow rate or water content over the range tested.

E. Marshall Space Flight Center, 1995¹⁵

In the mid-1990s, Marshall Space Flight Center developed the Multipurpose Hydrogen Testbed (MHTB). The test tank was a 3.05 m diameter by 3.05 m tall tank with 2:1 elliptical dome endcaps. The tank was insulated with 35.6 mm (1.4 inches) of SOFI and 45 layers of variable density MLI so that it could be purged with nitrogen instead of helium. The first 10 layers of the blanket were designed for 8 layers/cm, the next 15 layers were designed at 12 layers/cm, and the final 20 layers were designed at 16 layer/cm. The layer density variation was developed using varying numbers of Dacron netting bumper strips. The purpose of the testing was to demonstrate the survival of a full mission thermal profile. Thus on at least two occasions, rapid depressurization tests were performed. While there were figures published showing the heat load and pressure as a function of time, no analysis had previously been published on the total heat load the system had seen. Fortunately, the data had not been lost and was provided for further analysis. The first rapid depressurization test had an integrated heat load of 323 kJ/m^2 and the second test had an integrated heat load of 317 kJ/m^2 . It should however be noted, that during the second pumpdown there was an issue with the vacuum pumps stalling at the pressure of a few Torr for around 10 hours that added an extra 700 kJ/m^2 which has been subtracted out. While it was noted in the publication that it seemed like the second pumpdown went smoother and quicker, the actual applied heat load did not change much between the two tests.

III. Recent Testing

Over the last 10 years, testing high performance insulations systems throughout the various mission phases has returned. In addition to several liquid nitrogen based tests, a liquid methane test and a series of non-cryogenic tests were run.

A. Ball Aerospace, 2007-2009¹⁶⁻¹⁷

Focusing on MLI designs for liquid oxygen and liquid methane tanks, Ball Aerospace performed a series of rapid depressurization testing of their MLI systems on their 500 liter (0.85 m diameter) liquid nitrogen test article. All of the MLI were designed with 40 layers at a layer density of between 7 and 10 layers/cm. No foam substrate was included as it would not be needed to prevent nitrogen liquefaction on an oxygen or methane tank. Testing included one system with seam venting and one with perforations and slits, additionally tests on the perforated system were run with backfill of both nitrogen and helium gasses. Attempts were made during the non-perforated MLI test to measure the differential temperature between the inner MLI layer and the vacuum chamber and a central MLI layer and the vacuum chamber. Finally, two different pumpdown rates were tested.

In the initial phase of perforated MLI testing, the stagnant helium backfilled MLI (118 W/m^2) was shown to have a heat load that was 2 -3 times higher than what was achieved with the stagnant nitrogen backfilled MLI ($43 - 50 \text{ W/m}^2$). Similarly during the pumpdown, the integrated heat load was higher with helium gas in the MLI system (457 kJ/m^2 for helium, 364 kJ/m^2 for nitrogen). After rapid pumpdown, in all cases the MLI performance was seen to degrade 30 – 60% of the initial heat load (0.23 W/m^2 on the initial test to $0.30 - 0.36 \text{ W/m}^2$ on subsequent testing) with no noticeable difference between the helium and nitrogen testing.

In the second phase of non-perforated MLI testing (nitrogen backfill only), the depressurization performance was slightly worse at 404 kJ/m^2 for a rapid pumpdown and 480 kJ/m^2 for a slower pumpdown. This does indicate that for this design the perforations and slits were more efficient at venting the blanket and bringing the tank to steady state. Measurement of the pressure differential showed that in all cases, the pressure differential in the middle of the MLI was greater than at the tank wall when compared to the vacuum chamber (2.6 torr in the blanket versus 2.1 torr on the tank for the rapid pumpdown and 0.39 torr in the blanket versus 0.28 torr on the tank for the slow pumpdown). This was also much higher than the perforated pumpdown (0.08 torr on the tank for a slow pumpdown). This is inline with the predictions done by Lockheed in the 1960s that showed that due to the changes in viscosity of the gas, it was easier to evacuate a cold non-condensable vapor than a warm one.

Analytical attempts were made to predict the thermal performance of the system during rapid depressurization and these were not successful. The analytical model predicted an integrated heat load several times less than what was actually measured. This was mainly due to the measured boil-off flow rate not dropping off as quickly as predicted. While several items such as MLI thermal mass, blanket outgassing, and gas storage heat loads were investigated, none proved to have a large impact. The extra heat load was thought to be mainly due to the storage and slow release of energy in the tank walls (for which the testing was not set up to measure).

B. Methane Lunar Surface Thermal Control Testing (MLSTC), 2010¹⁸⁻¹⁹

The MLSTC testing was run at Glenn Research Center in 2010 to demonstrate the various thermal control scenarios that the Altair (lunar lander envisioned during the Constellation program) methane tanks would encounter during their trip to the moon. Of the environments tested, one was a rapid depressurization. While it was attempted to embed local pressure sensors within the MLI blankets at various locations, it was determined on breadboard testing that the sensors did not respond well. During data reduction, it was noticed that the heavy manway on the top of the tank accounted for a large quantity of the integrated heat load (956 kJ). This was because the thermal resistance of the conduction path connecting the tank lid to the liquid was of similar order of magnitude to that of the energy coming through the insulation. Thus the temperature on the lid increased during ground hold, but when a vacuum was pulled, the thermal resistance of the blankets were much greater than that of the conduction path and the temperature of the manway dropped, effectively dumping large amounts of heat into the liquid over a several day period. The total heat flux on the system at an atmosphere of pressure with a warm boundary temperature of 305 K was 52 W/m^2 and the total integrated heat load was 154 kJ/m^2 . An attempt was made at predicting the thermal performance of the MLI system thermal performance through the rapid depressurization test. The pre-test predictions were found to be unreliable. However, after adding the upper tank manway mass to the model, the predictions were much closer to the actual test performance. Figure 4 shows the model progression from pre-test to post test as well as the test data.

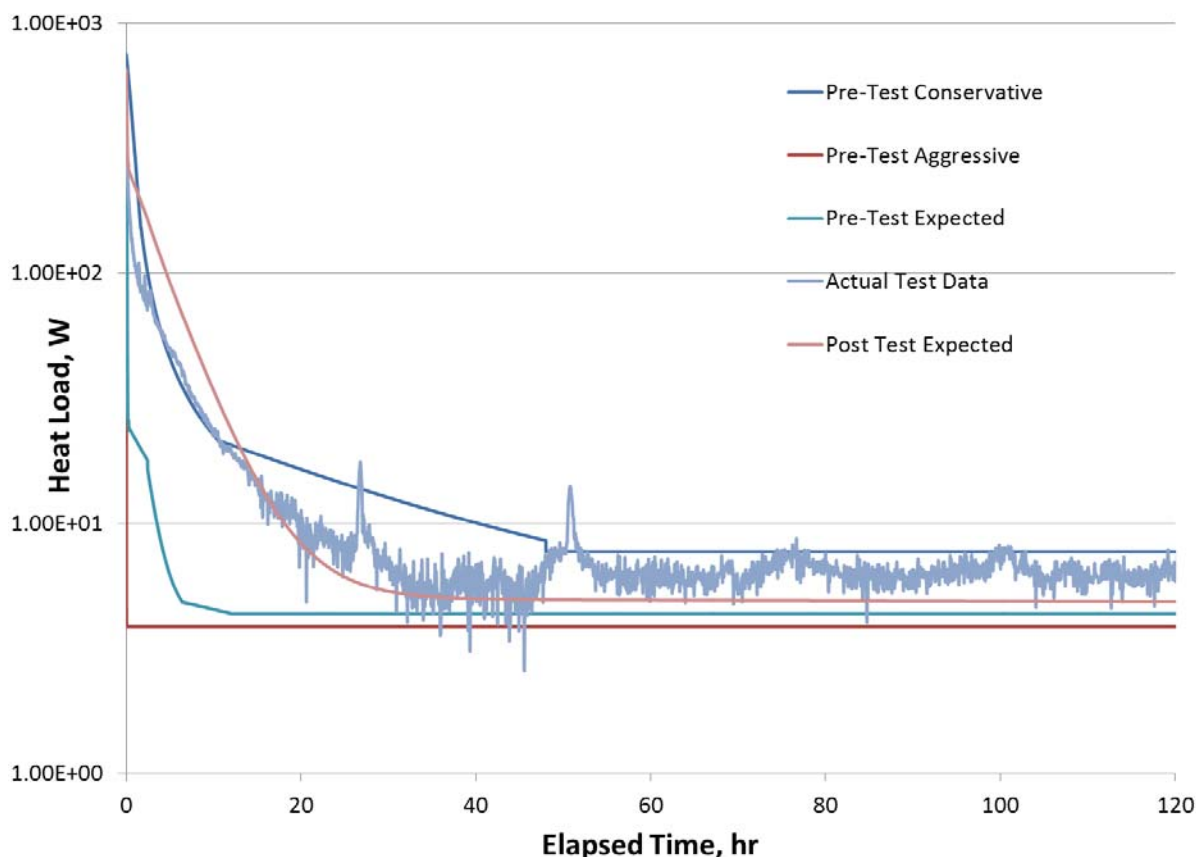


Figure 4. Modeling results from the MLSTC testing.

C. Glenn Research Center MLI/BAC Evacuation, 2011²⁰

In 2011, Glenn Research Center performed a series of rapid depressurization tests on 60 layer MLI panels with broad area cooling (BAC) shields. The objectives of the testing was to investigate any structural issues for supporting a broad area cooling shield during the rapid depressurization phase of flight. Testing only went from 101 kPa to approximately 2 kPa (20 Torr) and testing was at room temperature and with a heater on the back to increase temperature during some of the tests. Pressure measurements were made across the blanket to the vacuum chamber and there were two video cameras and a thermal (IR) camera to watch for blanket billowing during pumpdown and “hot spots” (when the heater was in use). Testing specimens ranged from MLI only, MLI with a BAC shield loosely floating in the MLI blanket, and MLI with a BAC shield firmly held down. Over 30 rapid evacuation tests were run using both nitrogen and argon gas. Three different pumping rates were testing and as with the Ball testing, it was observed that the faster the pump down, the earlier and larger the delta pressure spike within the MLI blankets. The largest pressure differential seen using gaseous nitrogen was 1.3 torr and with gaseous argon 1.5 torr. Argon always showed a slightly higher pressure drop due to the fact that the viscosity of argon is 25% higher than nitrogen.

IV. Cryogenic Boil-Off Reduction System Rapid Depressurization Testing

During recent Cryogenic Boil-Off Reduction System testing in the Small Multipurpose Research Facility (SMiRF) at Glenn Research Center in 2013, a series of rapid depressurization tests were conducted on the Self Supporting Multilayer Insulation (SS-MLI) test article. The testing was an attempt to gather system effects of installing a Broad Area Cooling (BAC) shield within a foam/MLI system. Testing was performed with liquid hydrogen with both gaseous nitrogen and gaseous helium as the “purge” gas. Neither purge was a constant flow purge, rather the gas was backfilled to maintain a constant pressure within the vacuum chamber prior to pumpdown. As such, they could be considered a stagnant purge or a backfill.

A. Test Article Design

The tank was a 1.2 meter diameter by 1.4 m long. The first layer of Spray on Foam Insulation (SOFI) was designed with the domes in a truncated cone shape to make MLI installation around the various flanges easier. The SOFI ranged from 19 mm thick around the cylindrical section of the tank to as thick as 0.1 m around some of the fluid lines on the top of the dome. On top of the SOFI was the inner MLI blanket consisting of 19 layers of Load Bearing MLI (LB-MLI) at a total thickness of 35.6 mm. The LB-MLI had a 0.01% open area perforation and was designed based on nitrogen flow through the blanket to survive the rapid depressurization. The function of the LB-MLI was to support the BAC shield, which was a distributed cooling network that was attached to a 90 K class cryocooler for other test objectives.²¹ On top of the BAC shield was 30 more layers of a more traditional MLI made of double aluminized polyethylene terephthalate reflecting shield (1% open), each reflector having two layers of polyester netting between them. The thickness of the outer MLI blanket was also 35 mm. The tank surface area was 6.2 m², the outer layer of MLI had an area of 7.3 m², the mean area of the insulation system being 7.07 m². The test article and insulation system are shown in Figure 5. A more detailed description of the insulation system and design parameters can be found in Johnson, Valenzuela, et.al.²²

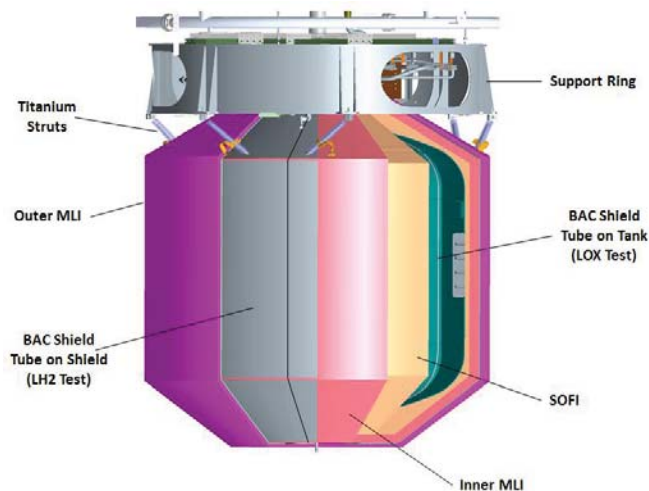


Figure 5. Tank Applied Insulation System.

B. Test Matrix and Test Operations

Four different tests were carried out, the first three were unsuccessful and the fourth was successful. The original intent of the test program was to perform the rapid depressurization testing using nitrogen gas as the backfill gas within the vacuum chamber. In order to define the rapid depressurization pressure profile, a “channel” was given to the SMiRF operators based on historical depressurization tests and the Space Shuttle payload bay depressurization rate (see Table 2).

Table 2. Pressure Channel for Vacuum Chamber Pressures.

Pressure (Torr)	Time – low (s)	Time – high (s)
760	0	0
700	6	20
600	15	30
500	20	40
400	28	50
300	35	60
200	50	75
100	60	100

The first test with nitrogen gas in the chamber started with the tank at approximately 90% full remaining from the previous boil-off testing at high vacuum. The chamber was backfilled with nitrogen gas to approximately 760 Torr (101.3 kPa) and the tank allowed to come to steady state before pumping down. All went smoothly for the first few minutes (the initial portion of the testing fit nicely into the provided channel) of depressurization, but the vacuum pumping rates became noticeably slow below 1 Torr (0.13 kPa). Since this kept the pressure within the MLI and thus the heat load on the tank higher, by the time the test crew returned the following morning, the liquid level was below 50%. As this would not allow for a successful completion of the testing, the test was terminated and the tank drained. Post test review of the temperature of 5 silicone diodes that were on the SOFI surface indicated a pooling of liquid turned solid nitrogen in the bottom of the MLI blanket on the SOFI surface. The solid nitrogen took at least 5 hours to sublimate by pumping it through the blanket (see Figure 6). While all other SOFI temperature point sensors remained above 100 K, liquefaction was not assumed to be on the bottom of the tank as the liquefaction could have occurred elsewhere away from the point sensors and flowed down the side of the tank before accumulating at the bottom.

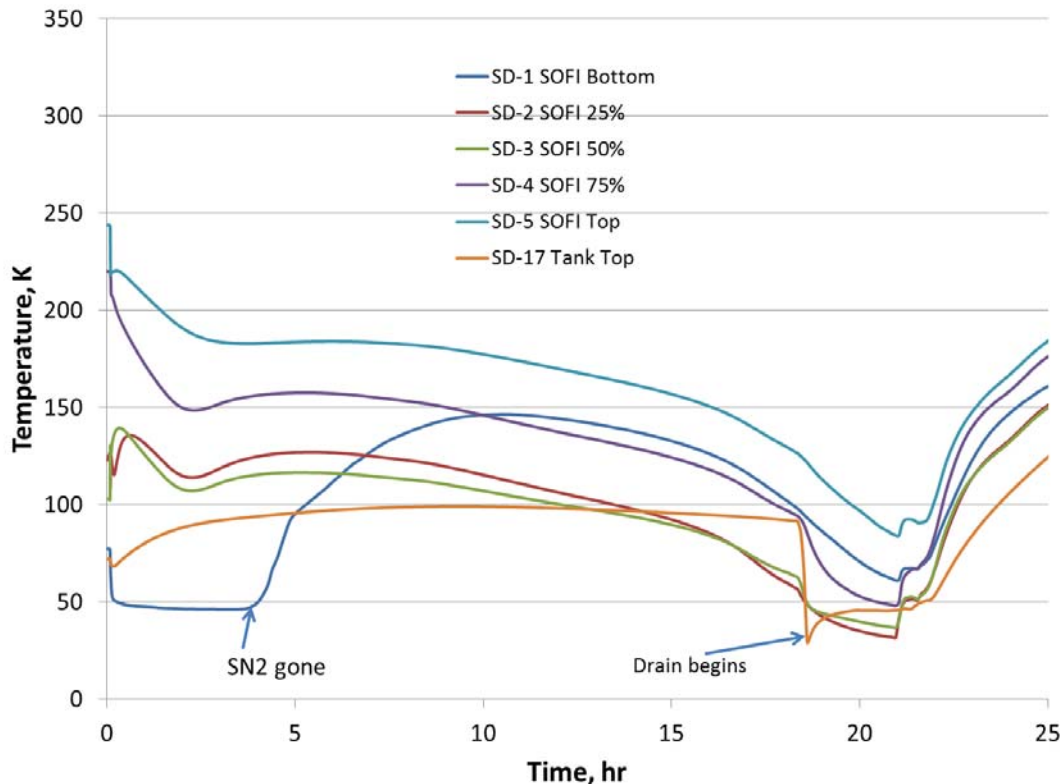


Figure 6. Foam surface temperatures during first rapid depressurization test attempt. Time elapsed from the start of the pumpdown.

Following the review of the first test data discussions were held as to what was the proper step going forward. A physical investigation of the insulation at this point would have been useful, but, due to the time required to remove the tank from the vacuum chamber and the MLI off of the tank, it would not have allowed for further testing. It was decided to try a test with the tank warm (not cold) in hopes that the liquefaction had been caused by test operations and breaking the vacuum on the foam while it was still cold from high vacuum testing (steady state high vacuum test data showed the foam at ~ 30 K). Additionally, it was desired to get pressure rise data to at sometime during the 760 torr test period to simulate tank conditions on the pad and how quickly tank pressure reacted to the high heat loads associated with gas filled MLI.

The second test was operated as described above (and shown in Figure 7). The tank was filled and then once the system was somewhat steady, the tank pressure was slowly raised to 138 kPa (20 psia). Then the tank was locked up for approximately 10.6 minutes (634 s) while the tank pressure rose from 159 kPa (23 psia) to 280 kPa (40.7 psia), for a pressure rise rate of 11.5 kPa/min. A majority of the heat was into the liquid on the bottom of the tank as indicated by LL-2, LL-3, and LL-4 rising the fastest despite being towards the bottom of the tank, furthest from the liquid-vapor interface. However, during pumpdown, the same issues with a slow pumpdown and solid nitrogen formation were seen as in the first test, and testing was halted after a few hours.

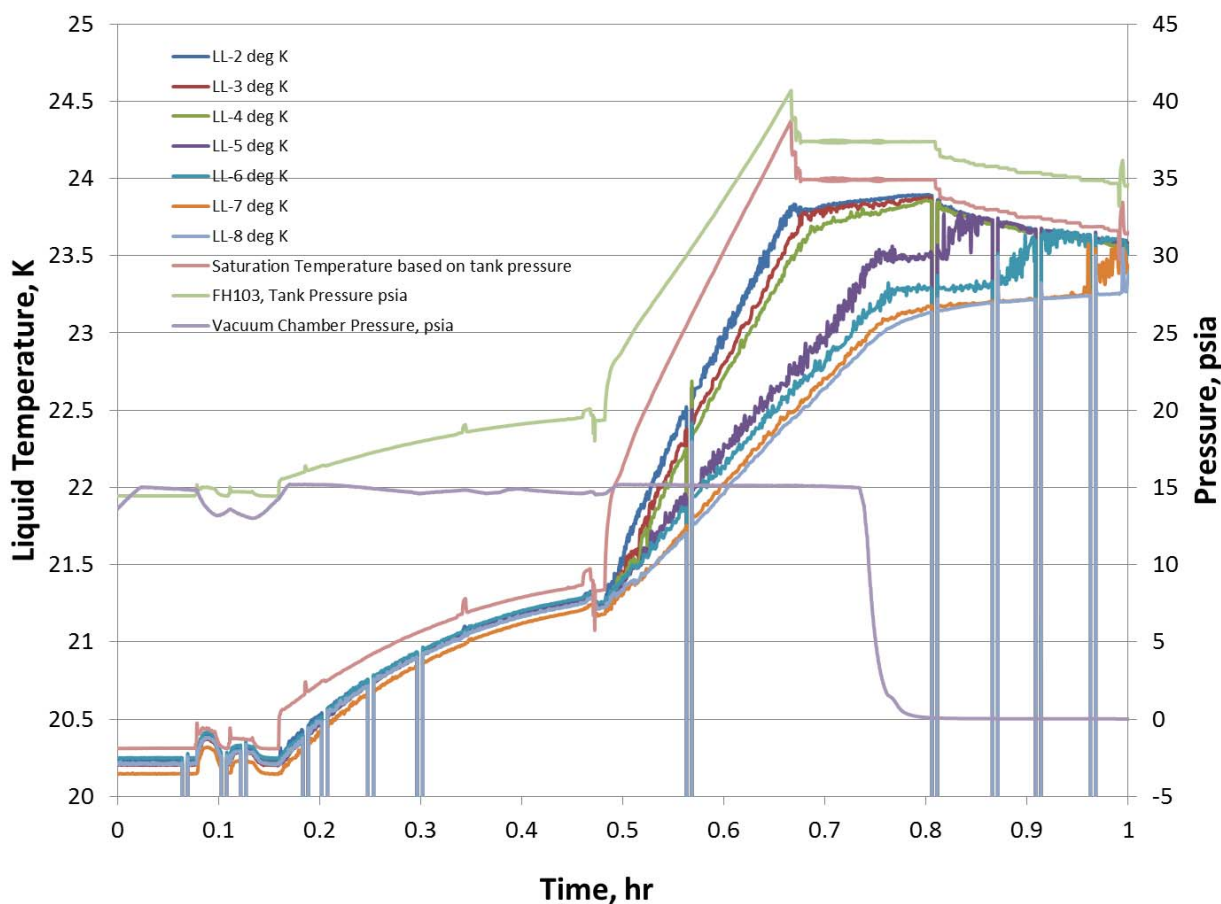


Figure 7. Tank pressure and liquid temperatures during pressure rise test with nitrogen background.

Following the second test there was further discussion on the forward test plan. The desire for a post-test foam and MLI inspection was growing rapidly. However, to hedge the possibility that the foam was too thin in some places (as opposed to having separated in others), it was decided to run a third and final test using helium as the backfill gas. The test would be run identically to the second nitrogen pumpdown (including pressure rise test).

The third test with helium ran nearly flawlessly. The depressurization of the vacuum chamber of the helium pumpdown is shown in Figure 8. The tank was filled to approximately 90 % full and topped off several times. SOFI temperatures all stayed well above 100 K. The pressure rise portion of the test was run for 10.8 minutes (647 s) and the pressure rose from 98.6 kPa (14.3 psia) to 290.5 kPa (42.2 psia), a pressure rise rate of 17.8 kPa/min (2.59 psi/min). Figure 9 shows the tank and fluid temperatures and pressures during the pressure rise period (the pump down started 7.4 minutes into the pressure rise test). It is interesting to notice that the liquid hydrogen was much more uniform in both temperature and temperature rise rate during the helium test (when compared to the nitrogen test).

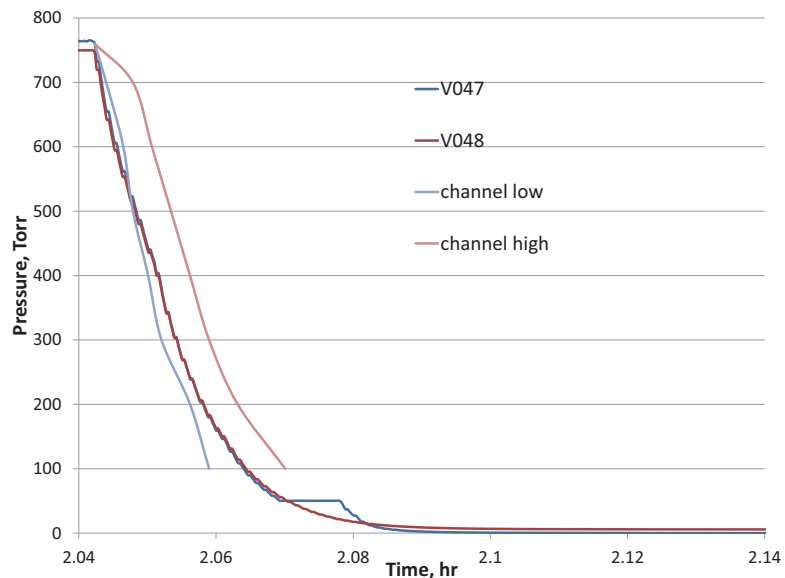


Figure 8. Pressure profile during helium rapid depressurization testing.

Post helium test analysis of the foam performance indicated that the foam was not too thin. SOFI surface diodes indicated that all surface temperatures were over 100 K. A post test dissection of the test hardware indicated several places in the thicker areas of the tank that the foam had cracked and even come loose (referred to as divoting) on the top of the tank. Several cracks were seen around the Velcro that was used to hold the LB-MLI in place. Uninsulated liquid feedlines in the tank that during the fill process at 1 atmosphere that would have contributed to the build up of liquid nitrogen running down the tank wall and pooling at the bottom.

The post test examinations and data analysis reinforced that for a rapid evacuation test using liquid hydrogen, everything must be properly insulated to prevent purge gas liquefaction and solification. The post test examination also brought a recommendation against spraying SOFI in thicknesses greater than approximately an inch to an inch and a half and also in general brought into question the capability of SOFI to function as a part of a rigid support structure for any external insulation loads. It is possible that adding more velcro may have solved the issue by reducing stresses on the existing Velcro attachments. Divoting was a common occurrence during shuttle flights and was attributed as the main culprit of the loss of STS-107 (Columbia).²³ As such, the foam issues were known, but accepted for this test program. The main cause of divoting and cracking in the foam is the difference in thermal expansion between the base tank material, the epoxy primers that allow the foam to stick to the base metal better and the foam itself.

After the pressure rise testing was completed, the tank was slowly let down to a constant back pressure of just under 20 psia at a rate that allowed the boil-off mass flow meters to read fairly close to their full scale range. This process took approximately 10 minutes and did lead to some uncertainty in the total integrated heat load on the tank due to flow meter reading.

The early pressure portion of the pumpdown fit well within the channel as shown in Figure 8. The vacuum chamber was less than a Torr in 3 minutes, it eclipsed 10^{-5} Torr within just over half of an hour and was in the 1×10^{-6} Torr range within a few hours.

C. Test Results and Discussion

Based on the mass flow meter data, the integrated heat load due to boil-off flow was calculated as shown in equation 1. The first term on the right hand side of equation 1 represents the entire heat load into the storage tank over a given time frame. The second term subtracts off the steady state flow rate for the same time (i.e. if the test tank had been directly inserted into orbit at steady state, as shown in Figure 1). Equation 1 was discretized to use the available data recorded at a given sample rate (once every second for the first 20 minutes, once every 5 seconds for the ensuing 10 minutes, once a minute through the following 15 minutes, and once every 5 minutes for the rest of the test) using equation 2.

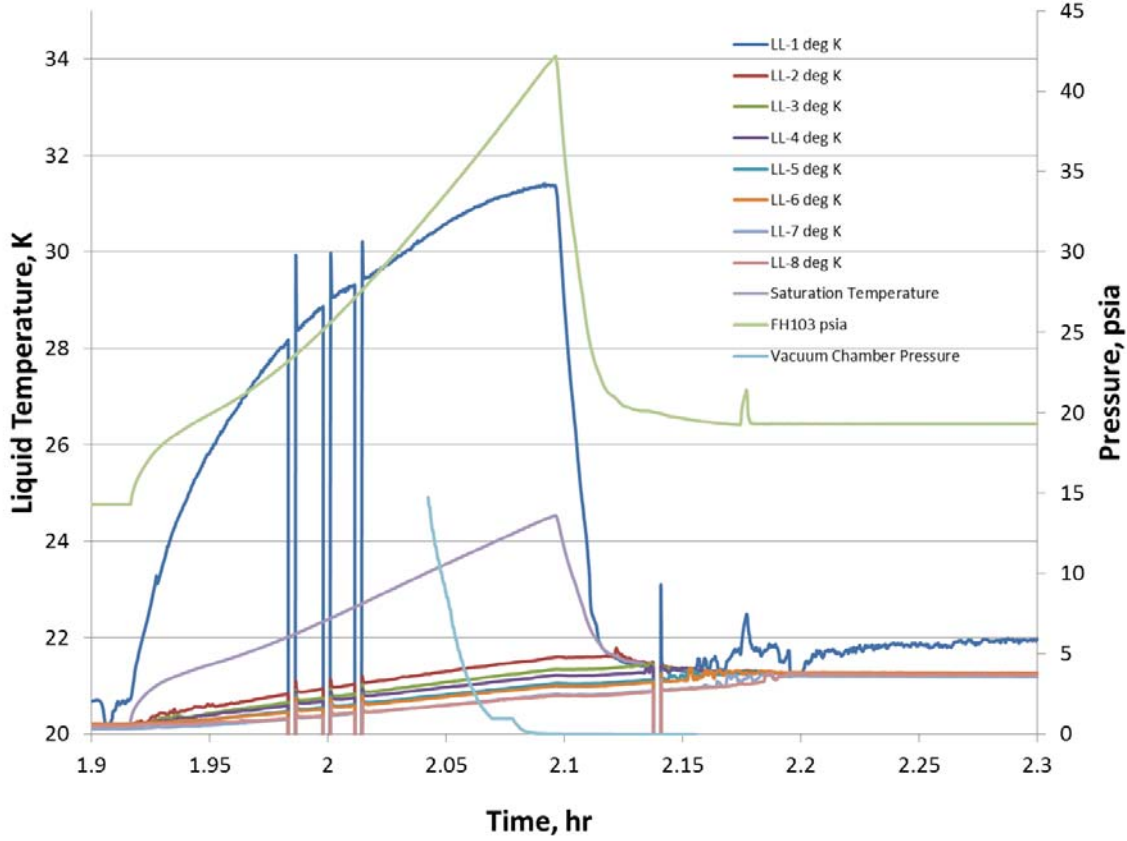


Figure 9. Temperature and pressures within the test tank during pressure rise testing with helium backfill gas.

$$Q = \int_{t=0}^{t=ff} \rho \dot{V}(t) [h_{Texit}(t) - h_{liq}] dt - \rho \dot{V}_{SS} (h_{Texit} - h_{liq}) (t_f - t_0) \quad (1)$$

$$Q = \rho \sum_{i=0}^{i=ff} [\dot{V}_i (h_{Texit,i} - h_{liq,i}) (t_i - t_{i-1})] - \rho \dot{V}_{SS} (h_{Texit} - h_{liq}) (t_f - t_0) \quad (2)$$

Several corrections were added based on how the actual test was conducted. The first relates to the liquid temperature change during the actual test (pressurization was allowed, and then that energy was vented off). The second relates to the period during the vent off, which can be calculated by including that time frame in equation 1, but also can be bound by ignoring that it existed (minimum) or assuming the on ground heat load was present the entire time (maximum). The net liquid temperature changes over the duration of the test are accounted for in equation 3. Since the liquid warmed up, the test tank also warmed up in the liquid region, however, as was noted by Johnson⁸ in the ullage region it cooled down, equation 4 shows how the net heat load was calculated. Equation 3 also allows the calculation of the energy absorbed during the locked up portion of the test, which is assumed to be essentially the ground heat load. Based on the eight liquid temperature sensors on the diode rake within the test tank, the bulk liquid mass was broken into eight nodes, analysis went from after the pressure from the pressure rise test had vented to the end of the test. Similarly, based on three tank surface sensors (two on the liquid and one on the ullage), the tank was broken up into three nodes for evaluation.

$$Q_{liq} = \sum_{j=1}^{j=8} V_j \bar{\rho}_j [h_{j,tf}(T_f, P_f) - h_{j,t0}(T_0, P_0)] \quad (3)$$

$$Q_{\tan k} = \sum_{k=1}^{k=3} m_k c_p (T)(T_{k,f} - T_{k,0}) \quad (4)$$

$$\bar{\rho} = \frac{\rho_{tf}(T_f, P_f) + \rho_{t0}(T_0, P_0)}{2} \quad (5)$$

1. Ground Heat loads

A comparison of ambient pressure test heat loads and parameters for the helium and nitrogen cases are shown in Table 3. The heat load for the nitrogen backfilled test was calculated based on the distributed liquid temperature sensors and determined to be approximately 2.64 kW, over twice the heat load as the helium test (1.21 kW). However, the pressure rise rate from the nitrogen test

Table 3. Summary of atmospheric pressure ground hold test data.

GN2 Press-Rise	GHe Press-Rise	
23.1	14.4	Initial Pressure, psia
21.4 (19.4)	20.2 (14.0)	Initial Temperature, K (Psat, psia)
0.49	1.92	Initial Time, hr
40.8	42.3	Final Pressure, psia
22.6 (27.0)	21.0 (17.6)	Final Temperatures, K (Psat, psia)
0.67	2.10	Final Time, hr
17.7	27.9	Pressure Rise, psid
0.18/10.6	0.18/10.8	Duration, hr/min
1.67	2.59	Pressure Rise Rate, psi/min
2.64	1.21	Calculated heat load, kW

was approximately 60% of the rate of the helium test. Since on a uniformly insulated tank, the pressure rise rate should be proportional to heat load, the awkward relationship between heat load and pressure rise rate of the indicates that there was a change in the heat load distribution between the liquid and vapor regions of the test article. More specifically, this points to the addition of heat load into the liquid portion of the tank from liquefaction and solidification of the nitrogen backfill gas.

2. Rapid Depressurization Heat Loads

Table 4 shows the summary of heat loads in the helium rapid depressurization test. The steady state energy input is 3.56 W over the approximately 69.5 hour test duration (the second term in equation 2). The integrated flow energy input is from the flow meter as calculated through the first term of equation 2. The tank temperature term is the results of the data calculated through equation 4 and the liquid temperature energy input is as calculated through equation 3.

Due to some time while the pressure was being released and flowing higher than the maximum flow of the flow meter (i.e. the flow meter was off-scale high), several different scenarios are accounted for. Using the data available the actual heat input into the tank was bounded using worst case assumptions and then a probable input was included. The minimum energy through the system is shown in the Total Min row, which is simply the sum of the Integrated Flow, Tank Temperature, and Liquid temperature terms. Then the Steady state term is subtracted in the second column and the energy input is normalized over the 7.07 square meter mean surface area of the tank. The final column shows at the normal boiling point, what percentage of the tank volume of liquid hydrogen would be boiled off. The energy input that was integrated during the unsteady time (the first 570 seconds of test) is shown next and the “Most Probable” line is merely the sum of the “Total Min” and the flow meter integrated over the unsteady time. The maximum heat load that could have come into the tank during those 570 seconds would be the steady state heat load at ambient pressure (1.21 kW). Applying that heat load over the 570 seconds and adding to the minimum heat load gives the total maximum heat load that could have been seen by the tank.

After the rapid pumpdown test came to steady state, the heat load was 3.56 W. This is only 0.24 W (7.3%) worse than the passive test earlier in the test matrix (prior to the rapid depressurization test). This shows minimal degradation after the blanket was put through several rapid depressurizations, including two where solid nitrogen was known to accumulate, making the pressure gradient on the blanket worse than normal (essentially the nitrogen outgassing through the blanket is what prevented the chamber from pumping down).

D. Comparison with Previous Testing

Comparing the multiple tests together, several general trends can be seen in Table 5. First, on the ground, the highest heat load is when a blanket is backfilled with helium gas underneath the blanket. Tests with just an external helium backfill show a decrease in heat low of a factor of at least 3 and maybe more, and active purge under the blanket has even further degradation in performance. Using nitrogen as a purge gas and purging or backfilling externally decreases the heat load by another factor of 2 – 3. However, there is not a large difference during the rapid ascent. The helium gas systems do have a slightly higher integrated heat load, but only by roughly 25%. While an MLI blanket can be damage to the blanket during rapid depressurization (as seen in the General Dynamics and McDonnell Douglas testing), if designed for, the blanket can easily survive multiple pressure cycles with minimal pressure gradients across them.

Table 4. Summary of integrated heat loads.

Approach	Total Energy Input (kJ)	Less SS Energy (kJ)	Energy Flux (kJ/m2)	Percent in tank loss
Steady State (at 890 vacuum)				
Integrated Flow*	1504			
Tank Temperature	41			
Liquid Temperature	534			
Total Min:	2080	1190	168	2.7%
Integrated During Unsteady Time**	197			
Most Probable:	2280	1390	196	3.2%
Steady State at 1 ATM for missing portion	696			
Total Max:	2780	1890	267	4.3%

* This does not include the first 570 seconds where the flow meter was very sporadic.

**This analysis is from the data gathered, the flow isolated from flow meter at the beginning of the test, but it was allowed to read high.

Table 5. Performance of all rapid depressurization tests for comparison.

Test Name	Tank Size (m)	# MLI Layers	Ground Heat Load (W/m ²)	Integrated Heat Load (kJ/m ²)	Max. dP in blanket (Torr)	Ratio of final and initial high vacuum heat loads	Number of Pressure Cycles
CBRS	1.2	49	171	196		1.07	3
MLI/BAC Venting	1.5 plate	66			1.3 (GN2) 1.5 (GAr)		30+
MLSTC	1.2	60	52	154			2
Ball Aerospace	1.2	40	118 (GHe) 50 (GN2)	457 (GHe) 364 (GN2)	2.6 (GN2)	1.3-1.6	3
NASA Marshall	3.05	45	64	320		1.00	2
NASA Lewis ¹	1.39	30	620			1.12	19
General Dynamics ¹	2.21	44				1.26	100
McDonnell Douglas ¹	2.67	70	860			1.5	1
Lockheed	0.38	115			0.62		2

¹Purge was underneath MLI blanket.

V. Conclusions

Recently during the Cryogenic Boil-off Reduction System testing a series of rapid depressurization tests were run using a flight representative methodology for integrating broad area cooling within the multilayer insulation system. They brought out several issues with the test methodology and design. After several failed nitrogen backfilled rapid depressurization tests, a successful helium backfill test was completed. The ground heat load with a static helium backfill was 171 W/m² and the integrated heat load during rapid depressurization was 196 kJ/m². The degradation seen in the insulation system after the rapid depressurization test series was just over seven percent.

A summary of all known rapid depressurization testing is presented along with the highlights from each test. The tests show several trends that indicate that the design of a insulation system designed for rapid depressurization is achievable. The measured pressure difference across the insulation blanket is low, the thermal penalty is on the order of 3 -5 days of steady state orbital heat loads, and blankets can survive multiple pressure cycles if the venting is properly allowed for. The body of data throughout the years brings a good basis for estimating system design for actual flight systems.

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